Energy of vanishing flow in heavy-ion collisions: Role of Coulomb interactions and asymmetry of a reaction

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(Dated: October 1, 2010)

We aim to understand the role of Coulomb interactions as well as of different equations of state on the disappearance of transverse flow for various asymmetric reactions leading to same total mass. For the present study, the total mass of the system is kept constant (A_{TOT} = 152) and asymmetry of the reaction is varied between 0.2 and 0.7. We find that the contribution of mean-field at low incident energies is more for nearly symmetric systems, while the trend is opposite at higher incident energies. The Coulomb interactions as well as different equations of state are found to affect the balance energy significantly for larger asymmetric reactions.

PACS numbers: 25.70.Pq, 25.70.-z, 24.10.Lx, 25.70.Mn, 21.65.Cd

I. INTRODUCTION

The heavy-ion physics has attracted much attention during the last three decades [1–5]. The behavior of nuclear matter under the extreme conditions of temperature, density, angular momentum etc., is a very important aspect of heavy-ion physics. One of the important quantity which has been used extensively to study this hot and dense nuclear matter is the collective transverse in-plane flow [1, 2, 6]. This quantity has a beauty of vanishing at a certain incident energy. This energy is dubbed as balance energy (E_{bal}) or the energy of vanishing flow (EVF) [6, 7]. This beauty is due to the counterbalancing of attractive mean-field at low incident energies and repulsive nucleon-nucleon (NN) collisions at higher incident energies. The balance energy of the masses ranging from $C^{12} + C^{12}$ to $U^{238} + U^{238}$ at different colliding geometries was studied experimentally and theoretically and found to be sensitive with the composite mass of the system [6, 8] as well as with the impact parameter of a reaction [6, 9, 10].

With the passage of time, isospin degree of freedom in terms of symmetry energy and NN cross section is found to affect the balance energy or energy of vanishing flow and related phenomenon in heavy-ion collisions [4, 5, 11, 12].

Experimentally, Pak *et al.*, studied the isospin effects on the collective flow and balance energy at central and peripheral collision geometries [11]. On the other hand, theoretically, this effect is studied by using the isospin-dependent Boltzmann Uehling-Uhlenbeck model (IBUU) [3, 5, 13], and isospin-dependent quantum molecular dynamics (IQMD) model [9, 12, 14, 15].

As noted, balance energy is due to the counterbalancing of the attractive mean-field and repulsive nucleon-nucleon collisions. The Coulomb interaction in intermediate energy heavy-ion collisions is expected to play a dominant role in balance energy due to its repulsive nature. These effects are supposed to be more pronounced in the presence of isospin effects [16]. The comparative study which will show the shift in balance energy due to Coulomb interactions in the presence of isospin effects by taking into account asymmetry of reaction in a controlled fashion is still missing in the literature. The second point is the asymmetry of the reaction. In some of the studies, the asymmetry of a reaction is taken into care, but not in other, which is very important to study the isospin effects [16, 17]. The asymmetry of the reaction can be defined by the parameter $\eta = \mid (A_T - A_P)/(A_T + A_P) \mid$; where A_T and A_P are the masses of target and projectile. The η = 0 corresponds to the symmetric reactions, whereas, non-zero value of η define different asymmetry of the reaction. It is worth mentioning that the reaction dynamics in a symmetric reaction ($\eta = 0$) can be quite different compared to asymmetric reaction ($\eta \neq 0$) [19]. This is due to the deposition of excitation energy in the form of compressional energy and thermal energy in symmetric and asymmetric reactions, respectively. The effect of the asymmetry of a reaction on the multifragmentation is studied many times in the literature [16, 17, 19]. Unfortunately, very little study is available for the asymmetry of the reaction in terms of transverse in-plane flow.

In this paper, we will perform the first ever study for the balance energy in terms of asymmetry of the reaction and then observe the effect of Coulomb interactions, symmetry energy, equations of state as well as different frame of references. The IQMD model used for the present analysis is explained in the Sec.-II. The results are presented in Sec.-III, leading to the conclusions in Sec.-IV.

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II. THE MODEL

The isospin-dependent quantum molecular dynamics (IQMD)[15] model treats different charge states of nucleons, deltas and pions explicitly [21], as inherited from the Vlasov-Uehling-Uhlenbeck (VUU) model [22]. The IQMD model was used successfully in analyzing the large number of observables from low to relativistic energies [12, 15, 21, 22]. One of its version (QMD), has been very successful in explaining the subthreshold particle production [23], multi-fragmentation [24, 25], collective flow [6, 26], disappearance of flow [6], and density temperature reached in a reaction [24]. We shall not take relativistic effects into account, since in the energy domain we are interested, there is no relativistic effect [27]. The isospin degree of freedom enters into the calculations via both cross sections, mean field and Coulomb interactions [22]. The details about the elastic and inelastic cross sections for proton-proton and neutron-neutron collisions can be found in Refs.[15, 27]. In this model, baryons are represented by Gaussian-shaped density distributions

$$f_i(r,p,t) = \frac{1}{\pi^2\hbar^2} e^{\frac{-(r-r_i(t))^2}{2L}} e^{\frac{-(p-p_i(t))^2 .2L}{\hbar^2}}. \quad (1)$$

Nucleons are initialized in a sphere with radius R $= 1.12A^{1/3}$ fm, in accordance with the liquid drop model. Each nucleon occupies a volume of $\hbar^3$ so that phase space is uniformly filled. The initial momenta are randomly chosen between 0 and Fermi momentum p_F. The nucleons of the target and projectile interact via two and three-body Skyrme forces and Yukawa potential. The isospin degrees of freedom is treated explicitly by employing a symmetry potential and explicit Coulomb forces between protons of the colliding target and projectile. This helps in achieving the correct distribution of protons and neutrons within the nucleus.
The hadrons propagate using Hamilton equations of motion:

$$\frac{d\vec{r_i}}{dt} = \frac{d<H>}{dp_i} \quad ; \quad \frac{d\vec{p_i}}{dt} = -\frac{d<H>}{dr_i}. \quad (2)$$

with
$<H>=<T>+<V>$ is the Hamiltonian.

$$= \sum_i \frac{p_i^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r},\vec{p},t) V^{ij}(\vec{r'},\vec{r}) \times f_j(\vec{r'},\vec{p'},t) d\vec{r} d\vec{r'} d\vec{p} d\vec{p'}. \quad (3)$$

The baryon-baryon potential V^{ij}, in the above relation, reads as

$$\begin{aligned} V^{ij}(\vec{r'}-\vec{r}) &= V^{ij}_{Skyrme} + V^{ij}_{Yukawa} + V^{ij}_{Coul} + V^{ij}_{Sym} \\ &= t_1\delta(\vec{r'}-\vec{r}) + t_2\delta(\vec{r'}-\vec{r})\rho^{\gamma-1}(\frac{\vec{r'}+\vec{r}}{2}) \\ &+ t_3\frac{exp(\mid \vec{r'}-\vec{r}\mid/\mu)}{(\mid \vec{r'}-\vec{r}\mid/\mu)} + \frac{Z_iZ_je^2}{\mid \vec{r'}-\vec{r}\mid} \\ &+ t_4\frac{1}{\rho_o}T_3^iT_3^j.\delta(\vec{r_i'}-\vec{r_j}). \end{aligned} \quad (4)$$

Where $\mu = 0.4fm$, $t_3 = -6.66MeV$ and $t_4 = 100MeV$. The values of t_1 and t_2 depends on the values of α, β and γ [2]. Here Z_i and Z_j denote the charges of the i^{th} and j^{th} baryon, and T_3^i, T_3^j are their respective T_3 components (i.e. 1/2 for protons and -1/2 for neutrons). The parameters μ and $t_1, ..., t_4$ are adjusted to the real part of the nucleonic optical potential. For the density dependence of the nucleon optical potential, standard Skyrme-type parameterizations is employed. The Skyrme energy density have been shown to be very successful at low incident energies where fusion is dominant channel [28, 29]. The Yukawa term is quite similar to the surface energy coefficient used in the calculations of nuclear potential for fusion [30]. The choice of the equation of state (or compressibility) is still a controversial one. Many studies advocates softer matter, whereas, much more believe the matter to be harder in nature [6, 22]. We shall use both hard (H) and soft (S) equations of state that have compressibilities of 380 and 200 MeV, respectively.

III. RESULTS AND DISCUSSIONS

As discussed earlier, asymmetry of a reaction is found to affect the phenomena of muti-fragmentation in intermediate energy heavy-ion collisions [17, 19]. On the other hand, system mass dependence of balance energy is studied many times in the literature [6]. To check the effect of Coulomb interactions and asymmetry of a reaction on the balance energy, we have fixed ($A_{TOT} = A_T + A_P = 152$) and varied the asymmetry of the reaction just like this: $_{26}Fe^{56} +_{44} Ru^{96}$ ($\eta = 0.2$), $_{24}Cr^{50} +_{44} Ru^{102}$ ($\eta = 0.3$), $_{20}Ca^{40} +_{50} Sn^{112}$ ($\eta = 0.4$), $_{16}S^{32} +_{50} Sn^{120}$ ($\eta = 0.5$), $_{14}Si^{28} +_{54} Xe^{124}$ ($\eta = 0.6$), $_{8}O^{16} +_{54} Xe^{136}$ ($\eta = 0.7$). The asymmetry of a reaction with multi-fragmentation in this fashion is varied many times [17, 19]. The whole reaction dynamics is studied at semi-central geometry by varying the incident energy between 50 and 250 MeV/nucleon with an increment of 50 MeV/nucleon by employing hard as well as soft equations of state. We have checked the stability of the reacting nuclei in laboratory (lab) as well as in center of mass (c.m.) frame by taking into account the Coulomb interactions. Our main purpose here is to understand the effect of equations of state and Coulomb interactions

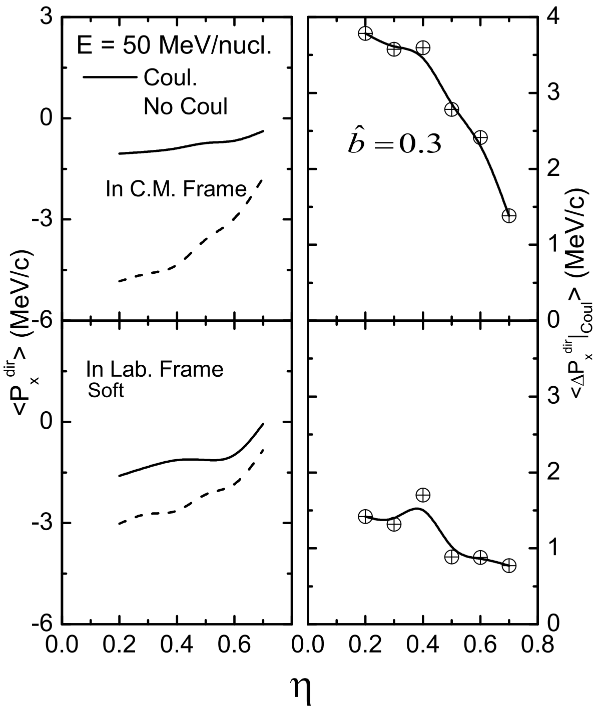

FIG. 1: Asymmetry dependence of directed flow in lab as well as center of mass frame in L.H.S, while, R.H.S for the relative effect of Coulomb interactions. The different lines in the figure are representing the effect of symmetry energy and Coulomb interactions.

on the energy of vanishing flow or alternatively, on the balance energy by taking into account the asymmetry of a reaction.

The directed transverse flow is calculated using $< P_x^{dir} >$ [6]

$$< P_x^{dir} >= \frac{1}{A}\sum_i sgn\{Y(i)\}P_x(i), \tag{5}$$

where Y(i) and $P_x(i)$ are, respectively, the rapidity distribution and transverse momentum of the i^{th} particle.

To check the effect of frame of reference, we display in Fig.1, variation of the asymmetry η on directed flow $< P_x^{dir} >$ in lab. as well as center of mass frame at incident energy of E = 50 MeV/nucleon. The top and bottom panels in the right hand side of the figure are representing the relative Coulomb effect with respect to the asymmetry of the reaction. This relative effect is calculated as:

$$< \Delta P_x^{dir} |_{Coul}>=< P_x^{dir} >_{Coul+Sym} - < P_x^{dir} >_{NoCoul+Sym} \tag{6}$$

As is evident from the figure, directed flow is found to increase in a systematic manner in C.M. as well as in lab frame at E = 50 MeV/nucleon with asymmetry of the reaction. The inclusion of Coulomb interactions does not alter the conclusions. Note that the increase in the asymmetry is related with the increase in the N/Z ratio. Because the symmetry potential for the neutron rich systems is stronger compared to the neutron poor systems due to large relative neutron strength. Furthermore, the symmetry potential is repulsive for neutrons and attractive for protons. On the other hand, more negative value of directed flow (dominating the mean field) is observed in the absence of Coulomb interactions in center of mass as well as in lab. frames. This is due to the enhancement of the chemical and mechanical instability domains in the absence of Coulomb interactions [32]. Similar type of study and conclusion was also performed for nuclear stopping in ref. [16].

Extensive study in the literature proves the stability of reactions in lab. frame, but, keep in mind that the reaction under consideration in these studies were symmetric in nature. As is clear from the figure, asymmetric systems are found to be more stable in the center of mass frame compared to the lab frame. Moreover, if one consider lab frame, one is surely missing the effect of asymmetry. To further strengthen the stability of center of mass frame with asymmetry, the relative effect of Coulomb interactions $< \Delta P_x^{dir} |_{Coul}>$ is studied in both frames. The relative effect of the Coulomb interactions is found to decrease with increase in the asymmetry of a reaction. The systematic decrease can be seen in center of mass frame with asymmetry, while very weak dependence of Coulomb interactions on the asymmetry is obtained in lab frame. For the further study, we have opted the center of mass frame because we want to see the shift in the balance energy due to Coulomb interactions, whose effect is clearly visible in center of mass frame.

Before we proceed further, let us check the time evolution of directed transverse flow. In Fig. 2, we display the time evolution of directed flow from E = 50 to 200 MeV/nucleon in center of mass frame for Soft (L.H.S) and Hard (R.H.S) equations of state. Note that the compressibilities of soft and hard equations of state are 200 and 380 MeV, respectively [2]. The time evolution is plotted in the absence of Coulomb interactions to see the maximum effect of asymmetry of a reaction on the directed in-plane flow. The figure reveals the following points:

a). The quantity $< P_x^{dir} >$ is observed to be constant throughout the whole distribution of time, while, the large variation is observed in the value at initial and final time steps when observed in the lab frame [6]

b). With the increase in the incident energy, the directed flow is approaching towards more positive value. This is due to the well known fact of increase in the frequent NN collisions with increase in the incident energy [6].

c). The behavior of the directed flow with asymmetry of a reaction follows the opposite trend at E = 50 MeV/nucleon as compared to other high incident ener-

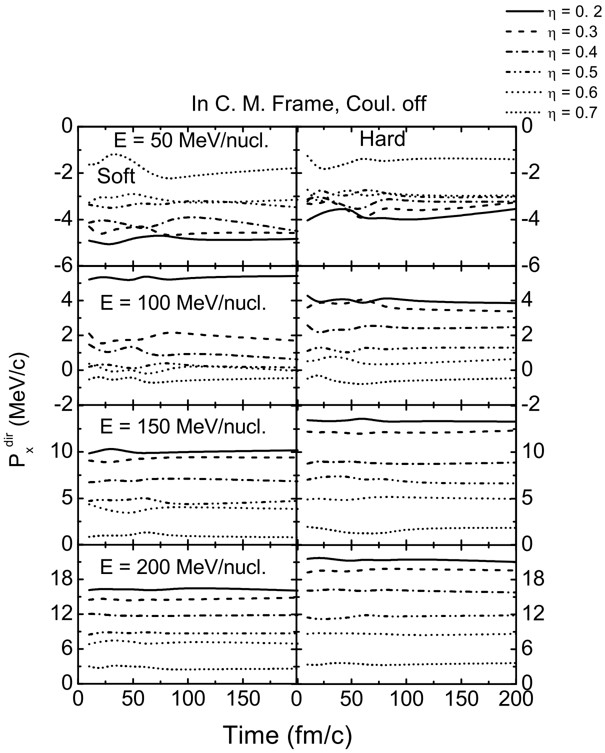

FIG. 2: The time evolution of directed flow at different incident energies in center of mass frame in the absence of Coulomb interactions. The left and right panels are for soft and hard equations of state, respectively.

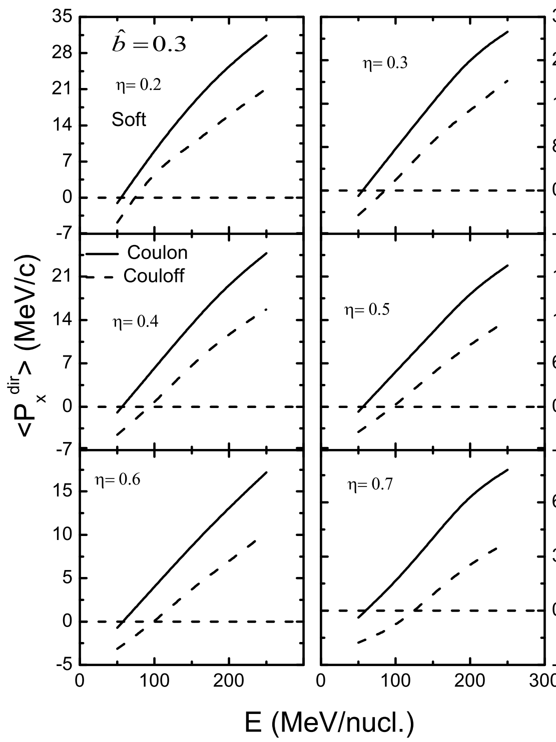

FIG. 3: Excitation function of directed flow at different asymmetries with and without Coulomb interactions at semi-central geometry.

gies. It has been discussed many times in literature and also clear from the present findings that attractive mean-field is dominating at E = 50 MeV /nucleon compared to higher incident energies under consideration [6, 33]. This is due to the different mechanisms contributing at low and high incident energies within isospin-dependent quantum molecular dynamics. It was shown by us as well as by others [4, 5, 12] that symmetry potential dominates the physics at low incident energy, while, NN cross sections one major driven force at higher incident energies. Furthermore, at low incident energies, symmetry potential is repulsive for neutrons and attractive for protons. With the increase in the asymmetry of a reaction, the number of neutrons increases and hence comparative repulsion due to neutrons also increases leading to less attractive value of the flow. It is also clear from ref. [17], that with the increase in asymmetry of a reaction, the participant zone decreases and spectator zone increases. At higher incident energies, where the effect of symmetry energy is negligible, the contribution of NN collisions comes from the participant zone whereas mean-field contribution comes from the spectator zone. Hence directed flow is found to be less positive with increase in the asymmetry of the reaction.

d). The directed flow has less positive value with soft equation of state compared to hard equation of state. The less positive means the dominance of mean-field. This is due to the different compressibilities of hard (380 MeV) and soft (200 MeV) equations of state. Naturally, more is the compressibility, more are the number of collisions and hence more positive is the directed flow. This is indicating that the directed flow is sensitive towards the equations of state.

Finally, in Figs.3 and 4, we display the excitation function of directed flow at different asymmetries from η = 0.2 to 0.7. The value of abcissa at zero value of $< P_x^{dir} >$ corresponds to the energy of vanishing flow (EVF) or alternatively, the balance energy (E_{bal}). The Fig. 3 shows the shift in the balance energy due to Coulomb interactions, while, Fig. 4 is representing the shift in the balance energy due to different equations of state. In Fig. 3, one sees a linear enhancement in the nuclear flow with increase in the incident energy. This increase in the transverse flow is sharp at smaller incident energies (upto 200 MeV/nucleon). If one goes to higher incident energies, the value gets saturated as discussed in ref [6]. We have displayed here the results upto 250 MeV/nucleon, since we are interested in and around balance energy. In the presence of Coulomb interactions, more positive value of the flow is obtained. This is due to the well known repulsive

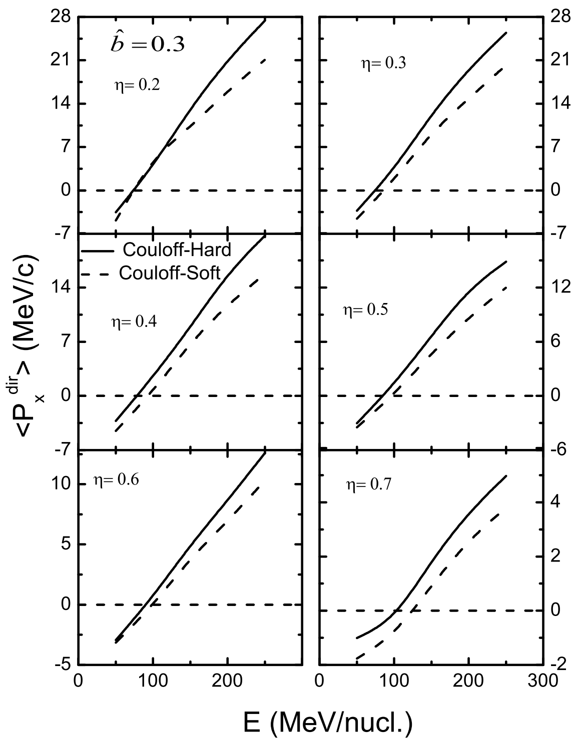

FIG. 4: Excitation function of directed flow with hard and soft equations of state in the absence of Coulomb interactions for different asymmetries.

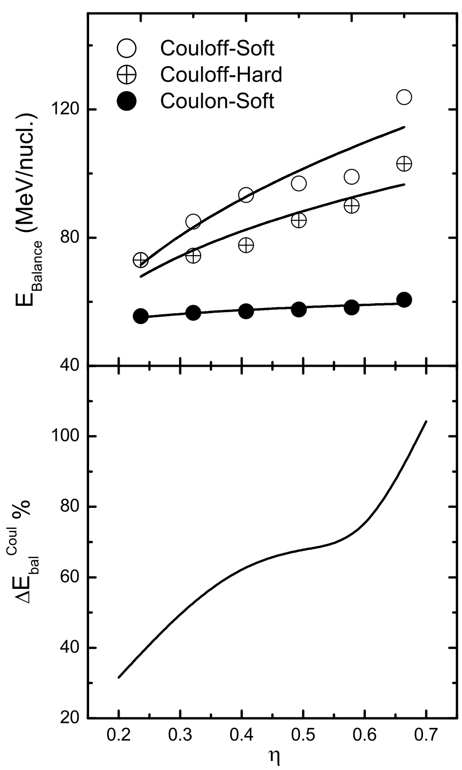

FIG. 5: Power law dependence of balance energy with asymmetry of the reaction. The lower panel is representing the relative % effect of Coulomb interactions on the balance energy.

nature of Coulomb interactions. At higher energies, the repulsion due to Coulomb interactions is stronger during the early phase of the reaction and transverse momentum increases sharply. The overall effect depends on the asymmetry of the reaction. If one looks at the balance energy, the shift in the incident energy towards the higher value is obtained at $< P_x^{dir} >= 0$ with the asymmetry of the reaction. This is showing that with increase in asymmetry of the reaction and in the absence of Coulomb interactions, attractive mean-field is dominating the large region of incident energy. The systematics of the balance energy with asymmetry of the reaction is discussed in Fig. 5.

As we have seen in Fig.2, that different equations of state show sensitivity towards the directed flow with respect to the asymmetry of a reaction. The detailed analysis with soft (S) and hard (H) equations of state is displayed in Fig. 4. The excitation function of directed flow follows similar trend as explained in Fig. 3. For nearly symmetric systems ($\eta = 0.2$), the balance energy is found to be independent of the equations of state, however, resonable differences are observed at higher incident energies. More positive values of directed flow are obtained with hard equation of state compared to soft equation of state. This is true at all asymmetries from ($\eta = 0.3$ to 0.7). This is due to different compressibilities of hard (380 MeV) and soft (200 MeV) equations of state. With an increase in the asymmetry of a reaction, the shift in the balance energy towards the higher value of incident energy takes place with soft equation of state compared to hard one. This is consistent with the findings in the literature [11].

To sum up, in Fig.5, we have displayed the asymmetry dependence of balance energy. We displayed the results for hard and soft equations of state by switching off the Coulomb interactions. In addition , for a comparative study, the results in the presence of Coulomb interactions with soft equation of state are also shown. All the lines are fitted with power law of the form $E_{bal} = C(\eta)^{\tau}$, where C and τ are the constants. The values of τ in the absence of Coulomb interactions for soft and hard equations of state are 0.375 and 0.282, respectively, while in the presence of Coulomb interactions for soft equation of state is $\tau = 0.06067$.

If we compare the asymmetry dependence of balance energy with mass dependence, the trend is opposite [6]. It clearly indicates that if one wants to study the isospin effect, then one has to consider the systems with $A_{TOT} = constant$, otherwise one is not able to get the exact information about the isospin effects. It

is also clear from the figure, that shift in the balance energy is observed due to Coulomb interactions as well as due to equations of state with asymmetry of the reaction. The shift is more due to Coulomb interactions in comparison to equations of state, indicating the importance of Coulomb interactions in intermediate energy heavy-ion collisions. The higher balance energy is obtained with Coulomb-off + soft equation of state followed by Coulomb-off + hard equation of state and finally Coulomb-on + soft equation of state.
For the further understanding, the relative percentage difference in the balance energy is plotted in the lower panel denoted by the quantity $\Delta E_{bal}^{Coul}\%$ given by

$$\Delta E_{bal}^{Coul}\% = \left[\frac{E_{bal}^{Couoff+soft} - E_{bal}^{Couon+soft}}{E_{bal}^{Couon+soft}}\right]\times 100 \quad (7)$$

The $\Delta E_{bal}^{Coul}\%$ is found to increase with the increase in the asymmetry of a reaction. This indicates shift of the nuclear matter towards the attractive mean-field region in the absence of Coulomb interactions with the asymmetry of the reaction. This difference $\Delta E_{bal}^{Coul} = 30$ MeV/nucleon at $\eta = 0.2$, while it is 115 MeV/nucleon at $\eta = 0.7$. The difference of 90 MeV/nucleon in the shift of balance energy with asymmetry cannot be ignored. This is the first ever study and experiments are called to verify the results.

IV. CONCLUSION

Our present aim was to understand the influence of Coulomb interactions as well as equations of state on the dynamics of large asymmetric reactions in semi-central heavy-ion collisions. At low incident energies, the contribution of mean-field is more for the nearly symmetric systems, while at higher incident energies, opposite scenario is observed. The balance energy is found to increase with the increase in the asymmetry of the reaction. The balance energy is affected by the Coulomb interactions compared to different equations of state.

V. ACKNOWLEDGMENT

This work has been supported by the grant from Department of Science and Technology (DST), Government of India, New Delhi, vide Grant No.SR/WOS-A/PS-10/2008.

VI. REFERENCES

[1] W. Scheid *et al.*, Phys. Rev. Lett. **32**, 741 (1974); K. G. R. Doss *et al.*, Phys. Rev. Lett. **57**, 302 (1986); W. Reisdorf *et al.*, Annu. Rev. Nucl. Part. Sci. **47**, 663 (1997).
[2] J. Aichelin, Phys. Rep. **202**, 233 (1991).
[3] L. Carlen *et al.*, Physica Scripta **34**, 475 (1986).
[4] L. W. Chen *et al.*, Phys. Lett. B **459**, 21 (1999).
[5] B. A. Li *et al.*, Phys. Rep. **464**, 113 (2008).
[6] A. D. Sood and R. K. Puri, Phys. Rev. C **69**, 054612 (2004); A. D. Sood *et al.*, Phys. Lett. B **594**, 260 (2004); A. D. Sood *et al.*, Eur. Phys. J. A **30**, 57 (2006); R. Chugh and R. K. Puri, Phys. Rev. C **82**, 014603 (2010).
[7] D. Krofcheck *et al.*, Phys. Rev. Lett. **63**, 2028 (1989).
[8] V. D. L. Mota *et al.*, Phys. Rev. C **46**, 677 (1992); G. D. Westfall, Phys. Rev. Lett. **71**, 1986 (1993); H. Zhou *et al.*, Phys. Rev. C **50**, R2664 (1994); H. Zhou *et al.*, Nucl. Phys. A **580**, 627 (1994); D. J. Magestro *et al.*, Phys. Rev. C **61**, 021602(R) (2000); D. J. Magestro *et al.*, Phys. Rev. C **62**, 041603(R) (2000).
[9] J. Lukasik *et al.*, Phys. Lett. B **608**, 223 (2005).
[10] J. P. Sullivan *et al.*, Phys. Lett. B **249**, 8 (1990); A. Buta *et al.*, Nucl. Phys. A **584**, 397 (1995); R. Pak *et al.*, Phys. Rev. C **53**, R1469 (1996).
[11] R. Pak *et al.*, Phys. Rev. Lett. **78**, 1026 (1997).
[12] S. Gautam *et al.*, J. Phys. G **37**, 085102 (2010).; S. Kumar, S. Kumar and R. K. Puri, Phys. Rev. C **81**, 014601 (2010); S. Kumar, S. Kumar and R. K. Puri, Phys. Rev. C **81**, 014611 (2010).
[13] B. A. Li *et al.*, Phys. Rev. Lett. **76**, 4492 (1996).
[14] C. Liewen *et al.*, Phys. Rev. C **58**, 2283 (1998).
[15] C. Hartnack *et al.*, Eur. Phys. J. A **1**, 151 (1998).
[16] J. Y. Liu *et al.*, Phys. Rev. C **70**, 034610 (2004); J. Y. Liu *et al.*, Chin. Phys. Lett. **21**, 1914 (2004).
[17] F. S. Zhang *et al.*, Eur. Phys. J. A **9**, 149 (2000); C. A. Ogilvie *et al.*, Phys. Rev. Lett. **67**, 1214 (1991); J. Singh, S. Kumar, and R. K. Puri, Phys. Rev. C **63**, 054603 (2001); M. B. Tsang *et al.*, Phys. Rev. Lett. **71**, 1502 (1993); A. Schuttauf *et al.*, Nucl. Phys. A **607**, 457 (1996); N. T. B. Stone *et al.*, Phys. Rev. Lett.**78**, 2084 (1997); B. Jackobsson *et al.*, Nucl. Phys. A **509**, 195 (1990); H. Feldmeier, Nucl. Phys. **515**, 147 (1990); A. Ono, H. Horiuchi, T. Maruyama, Phys. Rev. C **48**, 2946 (1993); *ibid.* **47**, 2652 (1993); P. B. Gossiaux, R. K. Puri, Ch. Hartnack, and J. Aichelin, Nucl. Phys. A **619**, 379 (1997); S. Kumar and R. K. Puri, Phys. Rev. C **58**, 320 (1998); *ibid.* **58**, 2858 (1998); *ibid.* **60**, 054607 (1999).
[18] J. Y. Liu, Y. F. Yang, W. Zho, S. W. Wang, Q. Zhao, W. J. Guo, and B. Chen, Phys. Rev. C **63**, 054612 (2001); J. Y. Liu, Y. Z. Xing, and W. J. Guo, Chin. Phys. Lett. **20**, 5 (2003).
[19] R. Donangelo *et al.*, Phys. Rev. C **52**, 326 (1995). S. Leray *et al.*, Nucl. Phys. A **531**, 177 (1991). S. Kumar *et al.*, Phys. Rev. C **68**, 1618 (1998). Y. K. Vermani *et al.*, J. Phys. G **36**, 105103 (2009). V. Kaur and S. Kumar, Phys. Rev. C **81**, 064610 (2010).

[20] C. A. Ogilivie *et al.*, Phys. Rev. Lett. **67**, 1214 (1991); M.B. Tsang *et al.*, *ibid.* **71**, 1502 (1993); R. T. de Souza *et al.*, Phys. Lett. B **268**, 6 (1991); N. T. B. Stone *et al.*, Phys. Rev. Lett. **78**, 2084 (1997); W. J. Llope *et al.*, Phys. Rev. C **51**, 1325 (1995).

[21] C. Hartnack, H. Oeschler and J. Aichelin, Phys. Rev. Lett. **90**, 102302 (2003); C. Hartnack *et al.*, J. Phys. G **35**, 044021 (2008).

[22] H. Kruse, B. V. Jacak, and H. Stöcker, Phys. Rev. Lett. **54**, 289 (1985); J. J. Molitoris and H. Stöcker, Phys. Rev. C **32**, R346 (1985); J. Aichelin and G. Bertsch, Phys. Rev. C **31**, 1730 (1985); C. Hartnack *et al.*, Phys. Rev. Lett. **96**, 012302 (2006).

[23] S. W. Huang *et al.*, Prog. Part. Nucl. Phys. **30**, 105 (1993); G. Batko *et al.*, J. Phys. G: Nucl. Part. Phys. **20**, 461 (1994).

[24] C. Fuchs *et al.*, J. Phys. G: Nucl. Part. Phys. **22**, 131 (1996); R. K. Puri *et al.*, Nucl. Phys. A **575**, 733 (1994).

[25] S. Kumar *et al.*, Phys. Rev. C **58**, 3494 (1998); S. Kumar, S. Kumar, and R. K. Puri, Phys. Rev. C **78**, 064602 (2008); J. Singh, S. Kumar, and R. K. Puri, Phys. Rev. C **62**, 044617 (2000); J. K. Dhawan and R. K. Puri, Phys. Rev. C **75**, 057601 (2007); J. K. Dhawan and R. K. Puri, Phys. Rev. C **75**, 057901 (2007).

[26] E. Lehmann *et al.*, Z. Phys. A **355**, 55 (1996); Y. K. Vermani, J. K. Dhawan, S. Goyal, R. K. Puri, and J. Aichelin, J. Phys. G: Nucl. Part. Phys. **37**, 015105 (2010); Y. K. Vermani, S. Goyal and R. K. Puri, Phys. Rev. C **79**, 064613 (2009); Y. K. Vermani and R. K. Puri, Eur. Phys. Lett. **85**, 62001 (2009).

[27] E. Lehmann *et al.*, Phys. Rev. C **51**, 2113 (1995); E. Lehmann *et al.*, Prog. Part. Nucl. Phys. **30**, 219 (1993).

[28] R. K. Puri and N. Dhiman, Eur. Phys. J A **23**, 429 (2005); R. Arora, R. K. Puri and R. K. Gupta, Eur. Phys. J A **8**, 103 (2000); R. K. Puri, M. K. Sharma and R. K. Gupta, Eur. Phys. J A **3**, 277 (1998; R. K. Puri and R. K. Gupta, Phys. Rev. C **51**, 1568 (1995); R. K. Puri, P. Chattopadhyay and R. K. Gupta, Phys. Rev. C **43**, 315 (1991); R. K. Puri and R. K. Gupta, Phys. Rev. C **45**, 1837 (1992); *ibid.* J. Phys. G: Nucl. Part. Phys. **18**, 903 (1992).

[29] R. K. Gupta *et al.*, Phys. Rev. C **47**, 561 (1993); R. K. Gupta *et al.*, J. Phys. G **18**, 1533 (1992); S. S. Malik *et al.*, Pramana J. Phys. **32**, 419 (1989); R. K. Puri, S. S. Malik and R. K. Gupta, Eur. Phys. Lett. **9**, 767 (1989).

[30] I. Dutt and R. K. Puri, Phys. Rev. C **81**, 047601 (2010); I. Dutt and R. K. Puri, Phys. Rev. C **81**, 044615 (2010); I. Dutt and R. K. Puri, Phys. Rev. C **81**, 064608 (2010); I. Dutt and R. K. Puri, Phys. Rev. C **81**, 064609 (2010);

[31] H. Stöcker and W. Greiner, Phys. Rep. **137**, 277 (1986).

[32] S. J. Lee *et al.*, Phys. Rev. C **68**, 014608 (2003); M. Colonna *et al.*, Phys. Rev. Lett. **88**, 122701 (2002).

[33] S. Kumar and S. Kumar, Chin. Phys. Lett. **27**, 062504 (2010); S. Kumar and S. Kumar, Pramana J. of Phys. **74**, 731 (2010).